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Performance measurements of a self-referencing interferometer wavefront sensor with optical amplification -- Briefing Charts (Preprint)

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Technical Paper

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14. ABSTRACT
The Self-referencing Interferometer Wavefront Sensor (SRI WFS) has been shown to outperform conventional wavefront sensors in strong scintillation environments. Recently, the Starfire Optical Range has developed a prototype SRI to evaluate its performance. This paper discusses the purposes of optically amplifying the reference beam. Specifically, it addresses regions of operation where gain improves signal-to-noise ratio (SNR) values, and thus the SRI WFS performance. Conditions are also addresses when Amplified Spontaneous Emission (ASE) from the optical amplifier degrades the overall signal, resulting in less than acceptable SNR ratios. Laboratory measurements of SRI WFS performance with an optical amplifier are presented.

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Good afternoon, my name is Laura Klein and today, I'm going to talk to you about the work I am doing in the characterization of optical amplification in the SRI WFS.

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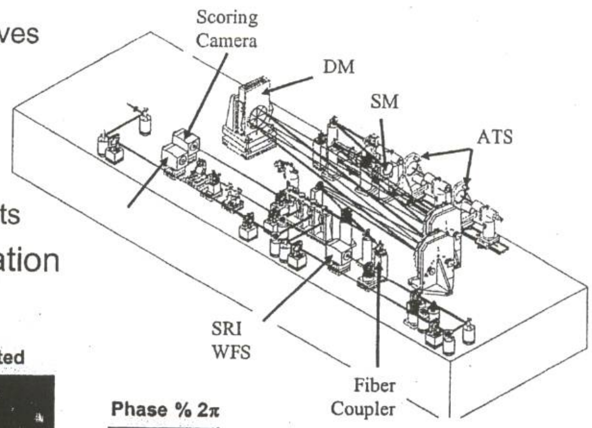
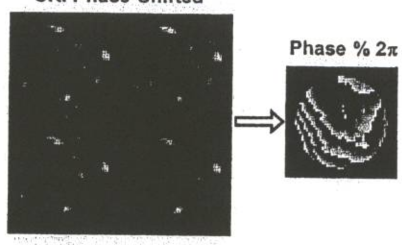
Introduction

- Project Overview
  - Motivation and Objectives
- SRI WFS
  - Design and Operation
- Optical amplification
  - Benefits and Constraints
- Laboratory Demonstration
- Experimental Results





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These are the topics I will cover, in the order I will cover them.

I will give a brief overview of the project – discussing its motivation and objectives.

Then I'll go over how the SRI WFS works and describe the laboratory experiment I conducted to test two optical amplifiers in the SRI WFS.

I'll end by showing some recent results we've obtained looking at the performance of the SRI WFS with the implementation of an optical amplifier.

SRI WFS with Optical Amplification

Motivation

- Performance of conventional AO degrades in strong scintillation
  - Shack-Hartmann WFS and least-squares reconstructor
  - Unable to accurately reconstruct wavefront due to branch points
- SRI WFS offers a solution to this wavefront sensing problem
  - Directly measures average optical field in each subaperture
  - Insensitive to scintillation
  - Amplify reference beam for better interference fringes

Objectives of Experiment

- Understand contributions of amplification in SRI performance
- Determine constraints and practical issues of real amplifiers

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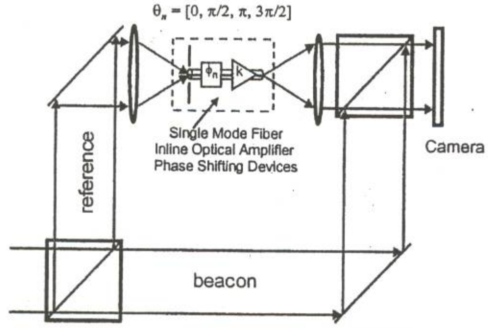
Wavefront sensors are an integral component in modern adaptive-optical systems. Wavefront sensors developed prior to the Self Referencing Interferometer Wavefront Sensor (SRI WFS), such as the Shack-Hartmann WFS, have limited application in strong scintillation environments, as the system's performance degrades due to branch points in the wavefront phase. The SRI WFS directly measures the average wavefront field of the incoming light over each subaperture of the WFS, making it theoretically immune to scintillation.\cite{rhoadarmer:04} Optical amplification of the WFS has been theoretically shown to enhance performance in the high scintillation Regime. By investigating the benefits and drawbacks of optical

amplification, laboratory results are presented to validate increased performance of the SRI WFS in strong scintillation.

SRI WFS Design & Operation

- Phase-shifting, point diffraction interferometer with amplified reference
  - couple part of beacon into SMF to create coherent reference
  - increase power in reference with optical amplifier
  - interfere amplified reference and beacon

$$I_n = I_{ref} + I_{beacon} + 2\sqrt{I_{ref}\, I_{beacon}}\; \cos[\phi_{beacon} + \theta_n]$$



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The SRI WFS is based on a phase-shifting, point diffraction interferometer. The figure shows a notional diagram of the SRI WFS.

The incoming beam, U_0, is split into two beams: a reference and signal, U_r and U_s, respectively. From there, the reference beam is coupled into a single mode fiber, amplified, and recombined with the signal to create interference

fringes on the WFS camera. Due to the broadband nature of Amplified Spontaneous Emission (ASE), several components are needed

in addition to the amplifier. After coupling into the single mode fiber, the resulting beam passes through an isolator, which will

prevent ASE from travelling backwards up the optical path, degrading the original signal, and corrupting other

detectors in the system. The beam is then optically amplified to improve the intensity of the signal. After the amplifier, a spectral filter is placed in the beam path to eliminate the extraneous wavelengths that add noise to the WFS measurements. After the spectral filter, the remaining portion of the reference beam is

phase shifted to provide the different interference patterns the SRI WFS will use to reconstruct the wavefront phase.

There are several methods of phase shifting that can be used to capture the necessary interference patterns. These methods include spatial

phase shifting, temporal phase shifting, and a combination of the two. Spatial phase shifting creates the interference patterns instantaneously, with four different beams

shifted at varying degrees and sent to different detectors. Temporal phase shifting takes the beam and phase shifts it in sequential integration periods of time,

and each image is recorded on a single detector. Spatial-temporal phase shifting combines both methods by capturing two images at two consecutive integration periods. Discussion and comparison of phase shifting techniques is discussed in a separate paper. Currently, the SRI WFS employs a fiber phase shifter that facilitates temporal phase shifting. After being phase shifted, the reference beam recombines with the signal beam, and the resulting beam is sent to the SRI WFS camera to create detectable interference patterns.

The ASALT lab operates with a signal wavelength of 1.55 microns. This is due to readily available parts, developed with technology matured by the telecom community. Both the semiconductor optical amplifier (SOA) and the erbium doped fiber amplifier (EDFA) employ a gaining meduim operating at a signal wavelength of 1.55

Why Optical Amplification?

An appropriate amount of gain helps the SRI WFS by boosting the intensity of the beam to overcome read noise of the WFS camera. In high scintillation environments or in situations with little illumination, the reference beam may not be intense enough to overcome read noise. Depending on the scenario, the beam may fluctuate in intensity, making tracking of the beam and detection of the interference fringes at the WFS difficult. Poor tracking prevents the necessary system stability to close and maintain the AO loop. Additionally, shallow fringes may preclude the possibility of reconstructing the wavefront phase from the interference pattern. Just as a generic amplifier increases the intensity of a signal, an optical amplifier increases the intensity of the optical signal. With a stronger reference beam, the depth of the fringes created on the SRI WFS can

become significantly greater than the background level of noise. This gives the needed signal to noise (SNR) levels for input to the WFS reconstructor; a necessary prerequisite for closed loop AO stability. Despite the benefits of gain in a closing an AO loop, there are drawbacks as well. Too much gain may boost the beam so much that it will

saturate the camera, thereby impairing the ability to take accurate measurements of the fringes.

Drawbacks of Optical Amplifiers

- Amplified spontaneous emission (ASE)
  - Broadband emission of photons from gain medium

$$P_{ASE} = (k-1)NF\frac{\Delta\lambda}{\lambda^2}\frac{hc}{\lambda}$$

  - Requires additional components to mitigate
    - Isolator
    - Spectral filter
    - Component insertion losses reduce effective gain
  - Additional noise sources
    - ASE photon noise
    - Beat noise → ASE-ASE and ASE-signal
    - Reduces effective well-depth of the camera
  - Mitigation options

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While amplifiers theoretically offer improved performance to the SRI WFS, they have some drawbacks. Additional components are required to mitigate spurious noise caused by the amplifying medium. As described in section 2, an isolator is vital to preventing incoherent interference with the amplified reference beam and the optical signal. A spectral filter can eliminate much, but not all, of the ASE from the remainder of the optical path. Adding these elements to the system introduces sources of loss that decrease the

overall signal, effectively lowering the gain of the amplifier. Even with splice connections, insertion losses and interfaces impair the system efficiency. Losses from the spectral filter, the isolator, and connections to these components are typically on the order of 4 dB.

Beat noise is an unavoidable part of ASE ASE that is approximately same wavelength as signal

Three ways to mitigate ASE:

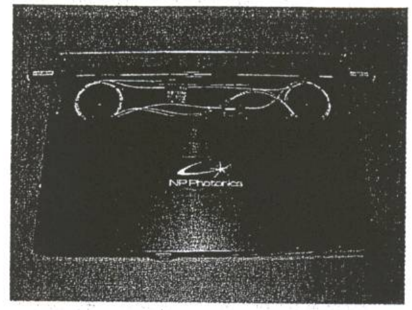
Reduce gain, k

Reduce NF

Narrow bandwidth spectral filter

Types of Optical Amplifiers

- Two amplifiers considered:
  - Semiconductor Optical Amplifier
  - Erbium Doped Fiber Amplifier
- Four factors of consideration:
  - Gain
  - Noise Figure
  - Path Length
  - Cost



Mini-EDFA prototype:
NP Photonics mini-EDFA
Gain: up to 39 dB
NF: $\leq$ 5 dB
path length: 68 cm

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Optical amplifiers receive a signal and send it through a gain medium, producing an output signal with increased power. Two optical amplifiers have been considered for use in the SRI WFS: the SOA and the EDFA. These amplifiers have unique trade-offs worthy of discussion. The major factors are: available gain, noise figure, optical path length, and cost.

GAIN

An EDFA can provide gains up to 50 dB while an SOA has a gain on the order of 15-20 dB. A first glance at the values favors the use of an EDFA, but this higher range comes with a price. ASE is linearly related to gain; therefore higher gain implies higher ASE. With a signal small enough to warrant the high gain from an EDFA, the amount of ASE introduced into the system may degrade any improved fringe intensity with an equally increased background noise.

NOISE FIGURE

The noise figure associated with an optical amplifier comes from several interactions between the signal and the gain medium. The lower the noise figure, the lower the minimum threshold of detecting the signal. Mathematically the noise figure is the ratio of the incoming SNR to the SNR of the amplified beam. Thus, amplifiers with lower noise figures are credited with better performance. The EDFA can have a noise figure of approximately 3.1 dB, whereas a SOA typically produces a noise figure of 9-10 dB.

PATH LENGTH

With the reference beam traversing a unique path, the signal must be path-matched to the reference path so that coherent beams arrive at the WFS camera. This path requires additional relay optics and table space. Depending on the length of the path, table space may become an issue, as well as maintaining mechanical stability of the additional optics. The SOA requires less than one meter of fiber to match the amplified beam path to that of the signal beam and to interface with the SRI WFS. A traditional EDFA requires upwards of 10 meters of fiber not only for the amplifier, but also for the signal leg to create the required path length to match that of the reference beam and produce interferometric fringes at the WFS camera.

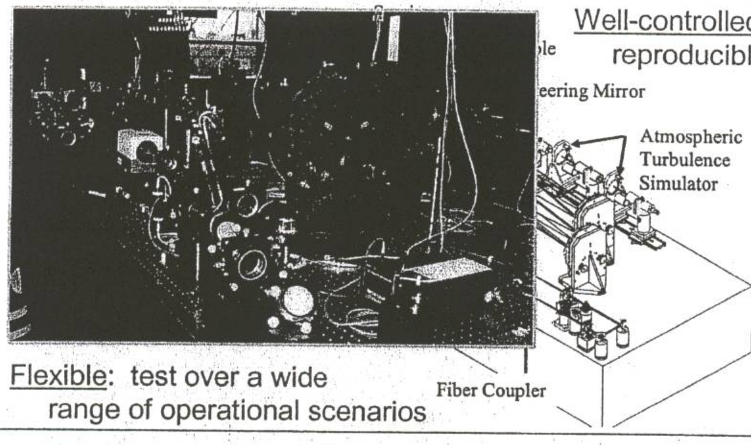
COST

While the above factors use performance as the primary metric, the last factor is a monetary consideration. The EDFA can cost upwards of \$15 thousand, while an SOA typically costs 3 or more times less, at around \$5 thousand. As mentioned in previous sections, additional components are necessary to the successful incorporation of an amplifier to the system. These components vastly differ in quality and complexity, and price will often scale with those characteristics, or highlight a lack thereof.

Laboratory Test & Evaluation Facility

- Atmospheric Simulation and Adaptive Optics Laboratory Testbed (ASALT)
  - laboratory environment for developing and testing AO technologies
    - WFS, DMs, control algorithms, AO configurations
  - Initial work focused on developing and evaluating SRI WFS

Well-controlled: calibrated and reproducible test conditions



Flexible: test over a wide range of operational scenarios

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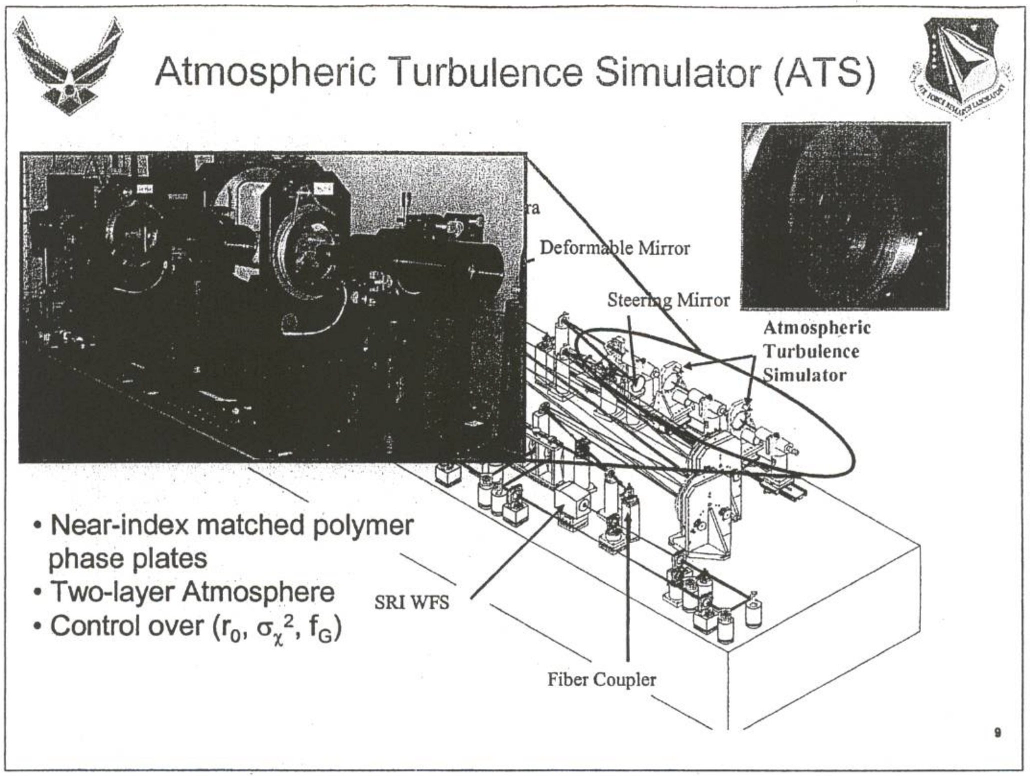
(Note: Underneath the picture is a 3D schematic drawing of the of optical setup. This schematic is also shown on following charts.)

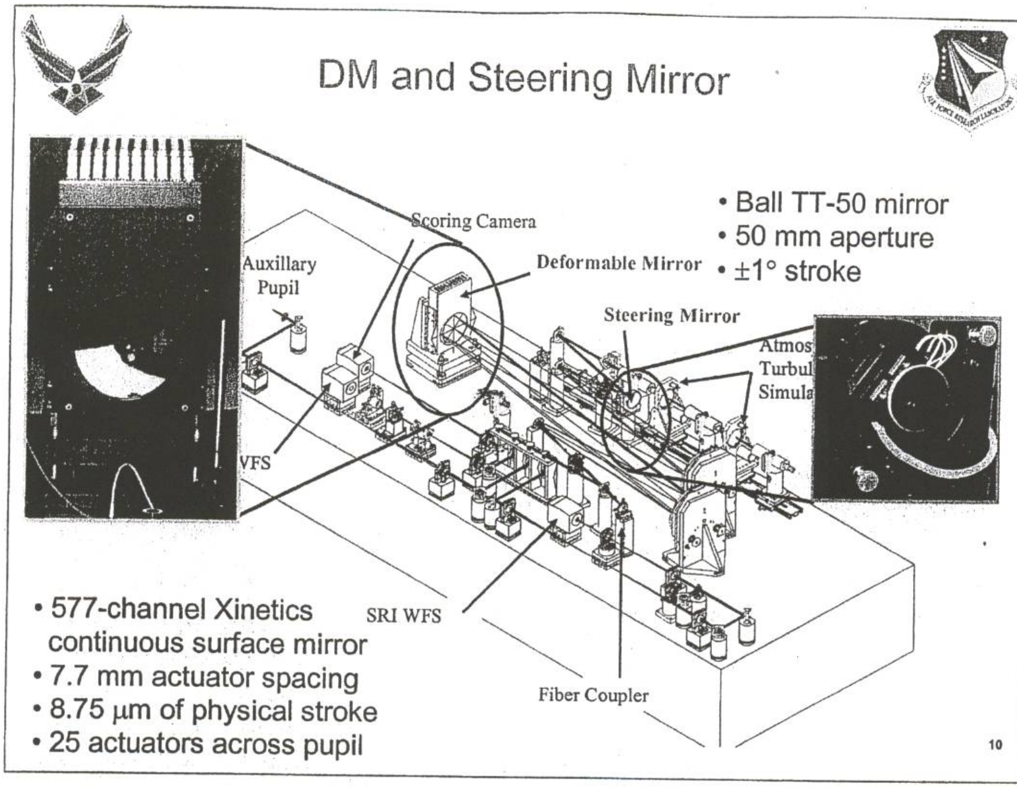
As I mentioned, the objective of this project is to develop an understanding of the practical issues involved in fabricating and operating a SRI WFS. To that end, we have been building a laboratory test facility for demonstrating the SRI WFS and evaluating its performance in hardware. The goal is to use the demonstration to strengthen our understanding of the SRI WFS and to validate and anchor the initial analyses and simulations we did.

To fully evaluate the SRI WFS over a wide range of configurations and component options, we have put together a platform where the SRI WFS could be evaluated in a realistic and reproducible environment. The result of our efforts is the Atmospheric Simulation and Adaptive-optics Laboratory Testbed, or ASALT for short. The goal of the design process for this lab, both in terms of optics and electronics, has been flexibility. The ASALT was designed to allow testing over a wide range of operational scenarios in order to evaluate SRI WFS performance and determine the most favorable design and configuration parameters. A schematic for the SRI WFS optical system is shown here. (click mouse for fly-in) And here is a picture of that setup.



A major element of the ASALT Lab is the Atmospheric Turbulence Simulator (ATS). This simulator allows us to test in the presence of atmosphericlike turbulence.

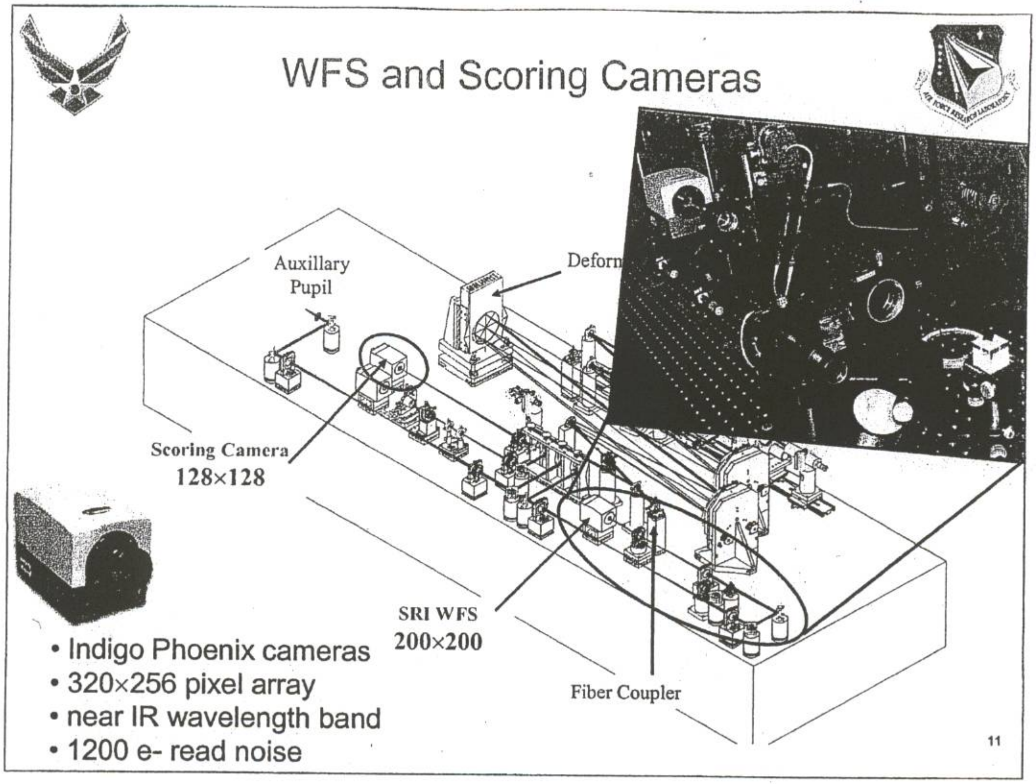
Pictures of the ATS design and hardware are shown here. The ATS simulates a two-layer atmosphere using static phase plates imprinted with Kolmogorov statistics. It is capable of simulating a wide range of atmosphericlike conditions. The design allows control of three atmospheric parameters—r_0, Rytov number, and Greenwood frequency.



The DM we are using is a Xinetics 577-channel continuous surface mirror with 8.75um of physical stroke and a 7.7 mm actuator spacing. Off-axis parabolas are used to relay and resize the beam before and after reflection from the DM. The system is designed with 25 actuators across the pupil.

The steering mirror is a 2" Ball (now Sapphire) tip-tilt mirror.

The DM is capable of operating at several kilohertz and the SM at several hundred hertz, but, because commercial IR cameras from Indigo are being used for the WFS and focal plane scoring cameras, the system frame rate is limited to a few tens of Hertz.

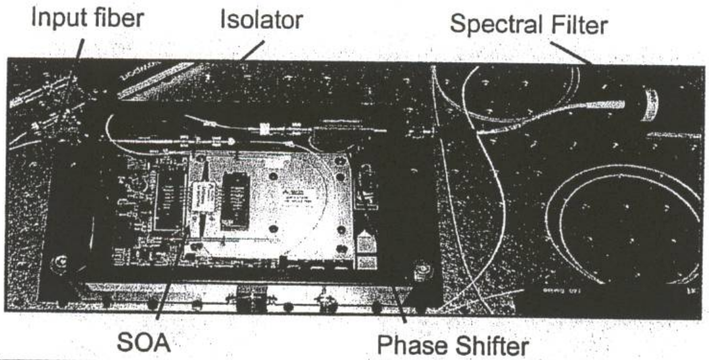


The testbed currently has two WFSs—an SRI WFS and a Shack-Hartmann WFS to allow comparison testing between the two.

As just mentioned, commercial Indigo cameras are used for both WFSs as well as the scoring camera. The resolution for each camera is given on the chart. The Shack-Hartmann WFS is a 24x24 sensor with 4x4 pixels per subaperture. Only the center 2x2 quad-cell is used with the remaining pixels forming a guardband to protect against subaperture cross-talk. The SRI WFS is a 200x200 sensor. This oversampling allows us to test with different resolutions at the WFS—25x25, 49x49, up to a hi-resolution 200x200 "truth" measurement. The scoring camera is 128x128 with a resolution of approximately lambda/4.

SRI WFS Reference

- Reference leg consists of...
  - Axon (now InPhenix) Semiconductor Optical Amplifier (SOA)
    - Gain ≤ 20 dB
    - Noise figure ≈ 9-10 dB
    - Length ≤ 1 m
  - General Photonics fiber optic isolator
  - General Photonics fiber phase shifter
  - Oz Optics tunable 0.3-nm spectral filter



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For the data I'm about to show, the SRI WFS is configured as described here. The components in the SRI reference fiber path include an optical isolator, a semiconductor optical amplifier (SOA), a fiber phase shifter, and a narrow-band (0.3 nm) spectral filter.

We can control the amplification of the SOA from 0 to almost 20dB by adjusting the pump current.

While the amplifier helps the SRI WFS work in low signal conditions, there is not free lunch. The amplifier spits out broadband amplified spontaneous emission (ASE). The isolator is needed to keep the ASE from feeding back into the system and corrupting the other sensors. The spectral filter is needed to filter out as much of the ASE as possible while simultaneously passing as much of the signal beam as possible.

Different phase shifts for the interferograms are created using the fiber phase shifter. Using this device, we can simulate different types of phase shifting, from spatial phase shifting to temporal phase shifting, using only one camera.

Optical Amplification Experiment

- Three levels of illumination
  - Only lowest two will be presented
  - highest illumination saturated camera
- Different pump currents for amplifiers
- One atmospheric scenario
  - $\frac{d_{act}}{r_0} = 0.75, \quad \sigma_\chi^2 = 0.5$
  - 250 frames of data per realization
  - Strehl averaged over last 150 frames
- No results for EDFA shown

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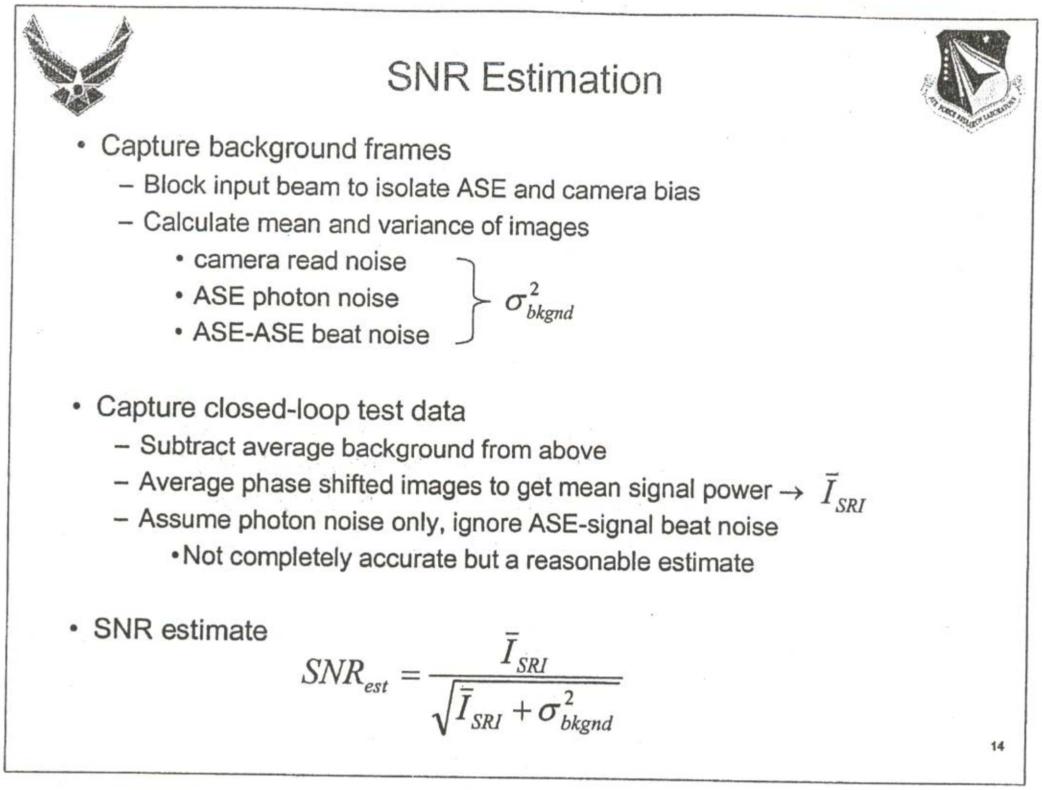
To characterize the effects of using an EDFA versus a SOA, we chose three illumination levels of light, ranging from a low level of 0.275 μW to 65 μW, which saturated the WFS camera. These values were selected by reading the full aperture power of the beam at the WFS. An attenuator placed in front of the ATS provided control for increasing and decreasing the light levels. The ATS was configured to simulate a scenario with Rytov of 0.5 and $\frac{d}{r_{0}}$ of 0.75. For every level of light, the beam ran through the turbulence and closed-loop data was collected. This process was repeated for four levels of amplifier gain. For the SOA, these values were 100, 150, 200, and 250 mA. To characterize the effects of the EDFA, the same process was implemented, replacing the SOA with the mini EDFA, shown in figure 4. For the EDFA the gain current values were 800, 830, and 850 mA. The EDFA and SOA values tested spanned the gains available for each amplifier. While three levels of illumination were tested, only the lowest two are used to compare performance of the EDFA against that of the SOA. With the EDFA, the maximum level of illumination saturated the WFS camera preventing true measurements of the interference fringes. With lower illumination levels, the relative intensity of the reference beam was so great compared to the signal beam that no fringes were detected on the WFS camera. As a result, no results for the EDFA can be presented.

Data for the amplifier testing was collected in standardized fashion. Through out testing the atmospheric scenario remained constant and is listed in Table~\ref{tbl:params}. For each amplifier setting, 250 frames of data were recorded, of which 175 were closed loop data. For each setting, only one realization was recorded. To calculate Strehl, the last 150 frames of data were averaged and compared against a reference average. To simulate the best case scenario of SRI performance, the reference average was closed loop data collected with no turbulence.

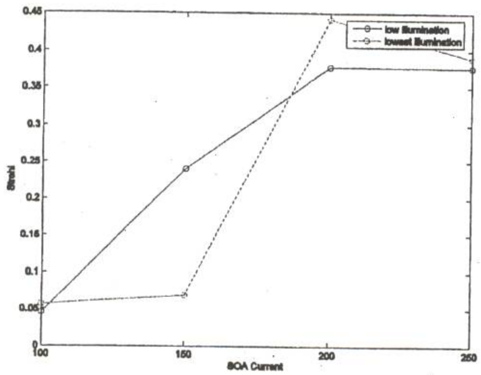


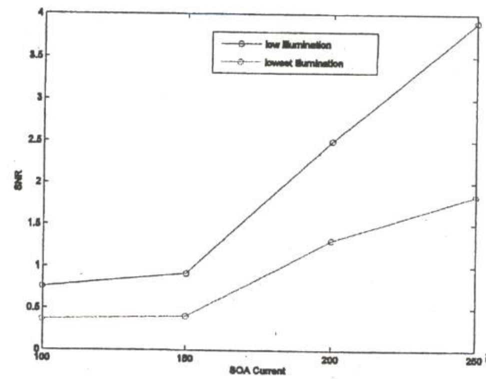
A standard analysis procedure was applied to all data collected to calculate the SNR of varying illumination levels. ASE background frames were captured for each amplifier level, where the signal beam was blocked before entry into the optical path. This isolated the ASE introduced into the system. These data frames were averaged to produce an ASE bias figure for each amplifier level. Additionally, the variance of this mean was calculated, using poisson statistics. Dark frames were also captured and the same process described above was applied to get an average value for the background noise. The value from the dark frames and the ASE bias frames were both subtracted from the signal value of the closed loop data for the corresponding amplifier level/illumination level data. This resulting value (I_{SRI}') was then used to calculate SNR as follows:

The variance of the closed loop data was assumed to be the variance of the ASE bias. The variance was also assumed to be photon noise only. While this is not an accurate representation, it is not disproportionate by orders of magnitude and therefore a reasonable estimate.

Experimental Results

- Examples with a semiconductor optical amplifier (SOA)
  - Two illumination levels
    - red illumination level ≈ 1.5 green illumination level
  - At weak signals gain improves performance by increasing SNR
    - threshold at $SNR_{est} \approx 1$
  - At lower illuminations unable to close track loop





This last bit of data shows the benefit of optical amplification.

The previous data we showed had plenty of signal because I wanted to separate out SNR issues. But here, we turned down the input power quite a bit to show that optical amplification can help performance. For the top set of images and red curve, once SOA amplification went above 10dB (producing an effective gain about 5 dB due to connector loss), the AO system was able to lock on. When we turned the power down a little bit more, the AO system didn't lock on until the SOA gain went above 15 dB (effective gain about 10 dB). We are currently working on determining the SNR conditions for these data so I don't have those numbers at this time.

We tried to turn down the light farther, but started having trouble with the tracker not locking on. For this data we had to turn up the tracker integration time as high as it would go and still we were only a few tens of counts above the background. We are looking at retaking this data and adjusting the system so we can vary the power going to the SRI without affecting tracker performance.

Closing Remarks

- Optical amplification can improve SRI WFS performance at low light levels
  - Balancing of benefits and drawbacks
    - Amplifier boosts power in reference beam
    - Amplifier adds noise to the SRI measurements
- Future efforts
  - SRI WFS testing without an optical amplifier
  - Testing with NP Photonics mini-EDFA
  - Improve SNR estimation to more accurately examine SRI noise performance
  - More in-depth examination of contribution of camera read noise

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In strong scintillation environments, optical amplification enhances signal detection and system performance. However, when light levels are intense enough, or when too much amplification is used, the resulting saturation of the WFS camera can degrade system performance. No EDFA data was presented in this paper, though an EDFA was tested in place of the SOA. At high illumination levels, the strong signal beam compounded by the amplification of the reference beam was so great it saturated the camera. At the lower light levels, the signal beam was so weak it went undetected at the camera. While the amplified reference beam could be detected at these low level regimes, interference fringes were not produced, preventing a successful closed-loop realization. Additional testing has been proposed, including removal of the amplifier altogether. Further testing will include determining a way to provide enough light for tracking purposes, and the EDFA testing will be re-conducted. Currently, the model used to estimate the SNR values is being modified and improved upon to achieve a more accurate realization.